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ENERGY STORAGE DEVICES--

ELECTROEXPLOSIVE DEVICES

1963

by

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FOREWARD

This report covers work carried out by Mr. J. L. Harms as a Research Assistant in the Design Division of the Department of Mechanical Engineering. It was supported by the Jet Propulsion Laboratory, Pasadena, California, under Contract No. 950535. My own contributions to the report are primarily of an editorial nature.

P. Z. Bulkeley

INTRODUCTION

In the past few years, small electroexplosive devices (EED's) have become increasingly important to the missile and aerospace industries. This is because of their high ratio of power to weight and size and to their rapid functioning time compared to most other power-producing devices. The purpose of this report is to explore the present state of the electroexplosive art. It confines itself to "off the shelf" devices and unclassified information.

Electroexplosive devices are used for ignition, actuation, or initiation. Devices of the ignition class are, generally, electric matches or igniters whose primary function is to produce flame and heat for igniting rocket propellants or larger explosive charges. Igniters are generally the smallest of the many types of EED's because of the simplicity of their function. In the actuator class are devices which perform some mechanical function such as moving a piston, operating a switch, cutting a cable, or opening a valve. They are non or low-brisance devices and function through pressure impulse or by gas pressure generation. The initiator class of devices are more brisant. It includes primers, detonators, and other devices which transmit considerable explosive force. They are generally used in explosive trains, high-explosive initiation, destruct and space vehicle separation units. Initiators use high-pressure shock waves to accomplish their function, and incorporate secondary explosives in their explosive charge.

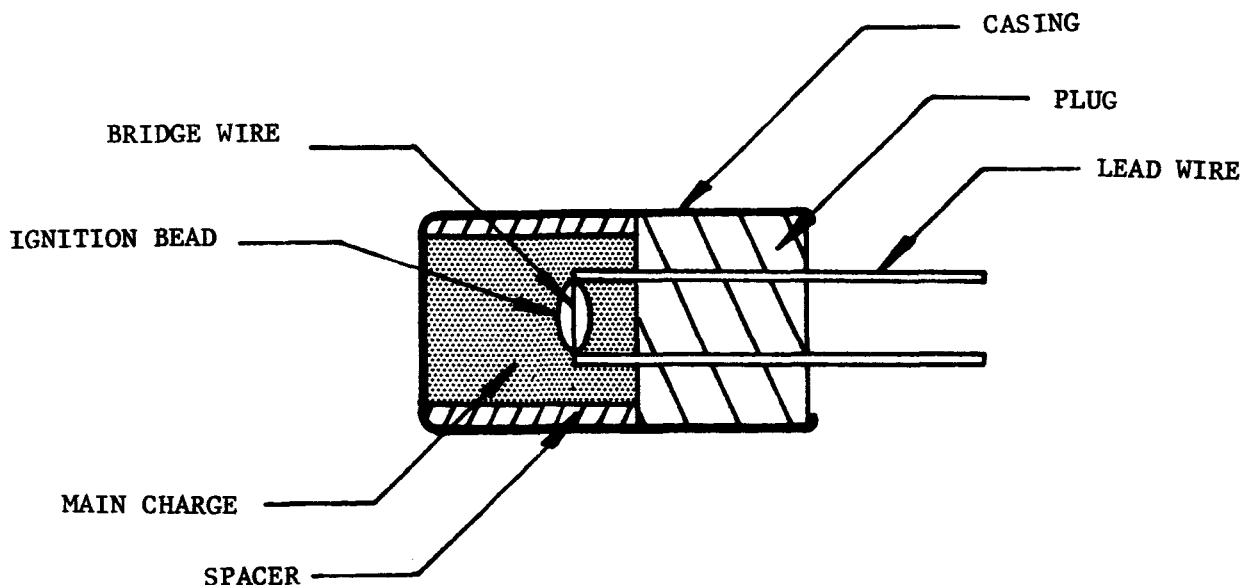


FIGURE 1. SCHEMATIC DIAGRAM OF SQUIB IGNITER

Squibs fall under the general heading of igniters. They have little brisance and find their principle use in lighting low-power explosives and propellants or in igniting the charge of a larger igniter device. Squibs come in many sizes and shapes and have some applications as low pressure (200-500 psi) pressure cartridges.

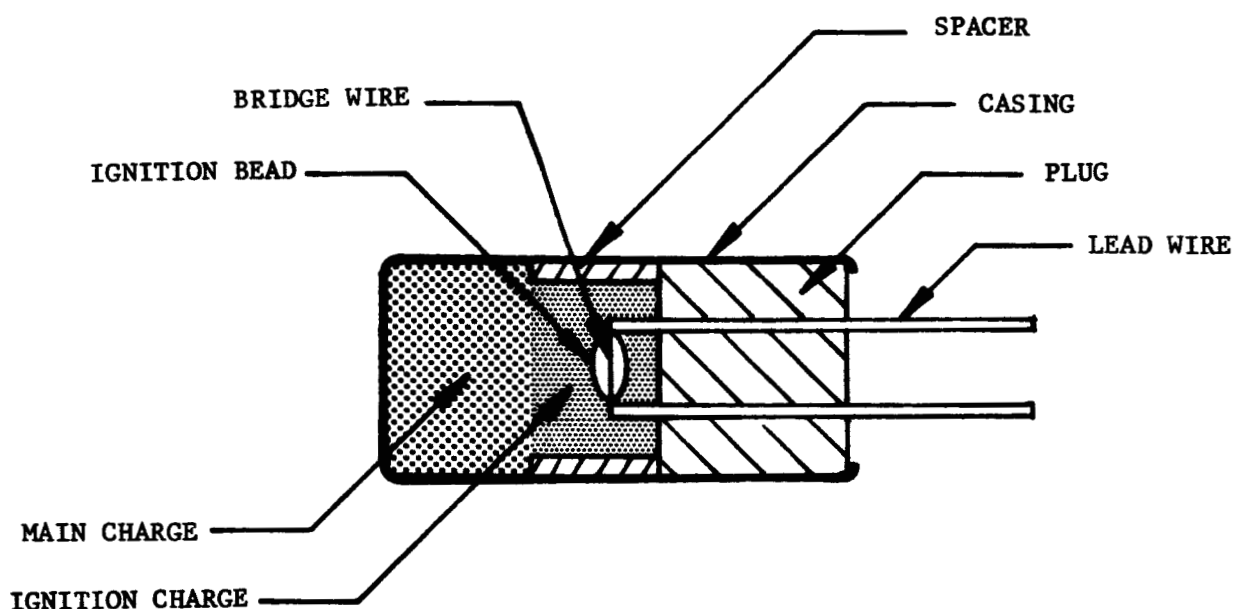


FIGURE 2. SCHEMATIC DIAGRAM OF PRESSURE CARTRIDGE

The actuator group includes pressure cartridges, gas generators, dimple motors, piston actuators, bellows motors, and cable cutters (or guillotines). Pressure cartridges are useful power sources for generating a large pressure pulse, i.e., a high pressure for a short interval of time. This pressure is the result of the high temperature gas generated in the cartridge. After a time, heat transfer to its surroundings reduces the internal pressure nearly to ambient. These devices are extremely useful in valve and thruster operations. They are one or two inches in length and weigh one or two ounces.

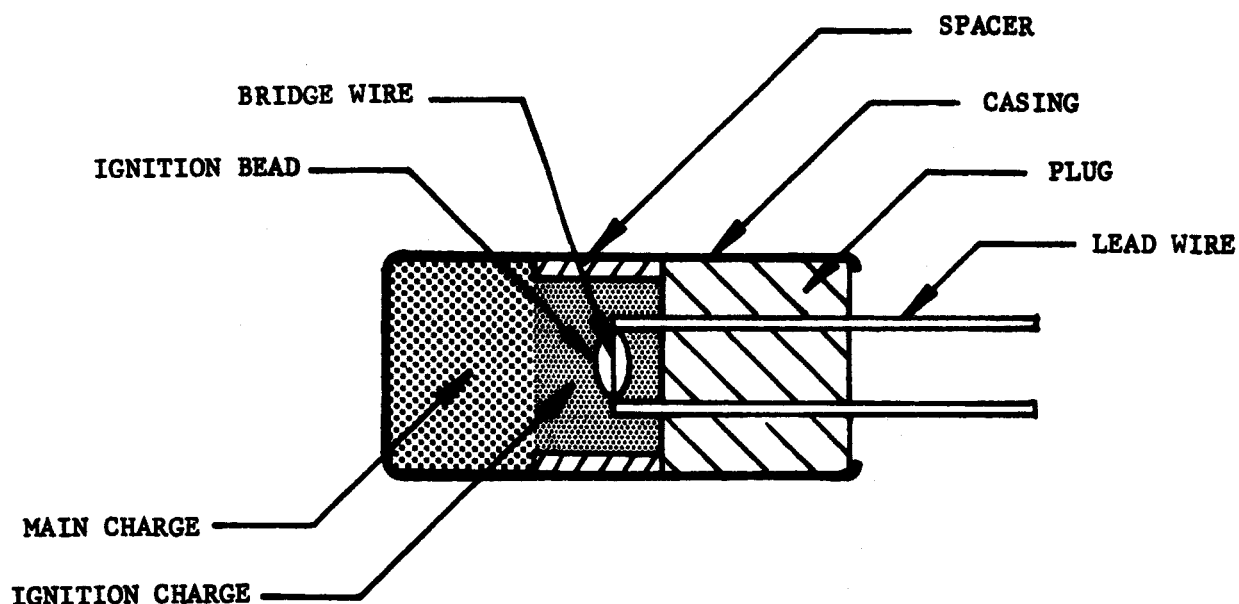


FIGURE 3. SCHEMATIC DIAGRAM OF GAS GENERATOR

Gas generators range upward in size from that of a small squib to several inches in diameter and several inches in length. These devices differ from pressure cartridges. They produce a continuous pressure; a high residual pressure remains after heat transfer because of the production of gaseous combustion products. Generators can be made to produce constant, increasing or decreasing pressure over a time interval. The interval can be several milliseconds for squib-size generators to many seconds on larger models. Small gas generators are used quite extensively to charge liquid cell batteries by displacing electrolyte into the battery. Larger types are used extensively in supplying pressure to hydraulic and similar systems.

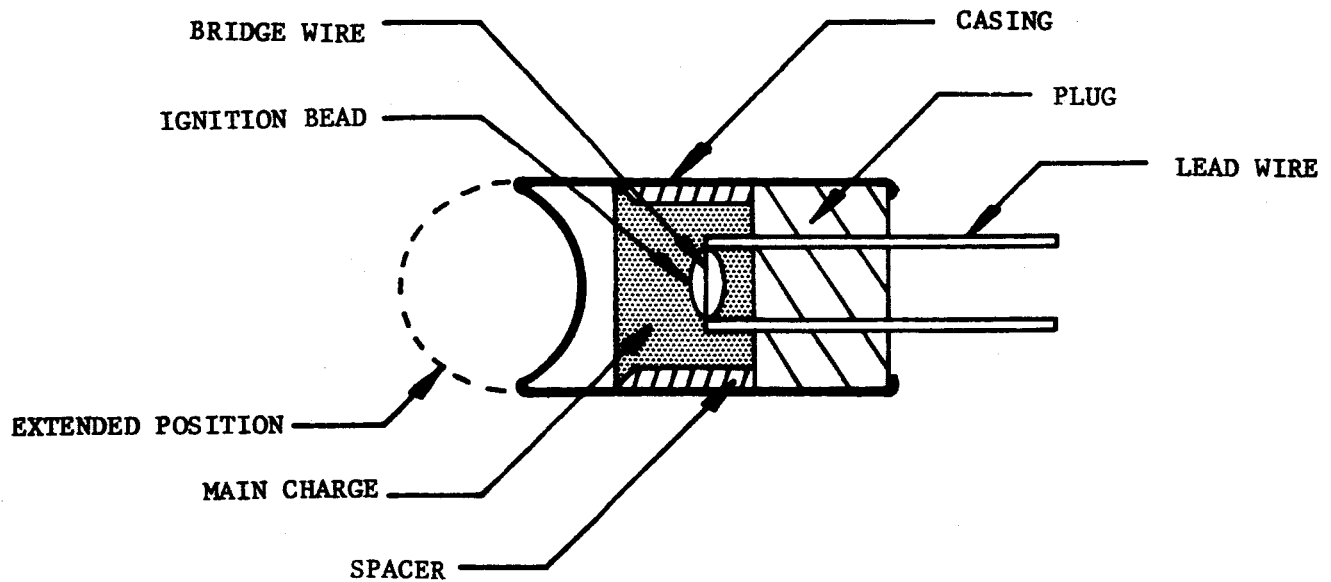


FIGURE 4. SCHEMATIC DIAGRAM OF DIMPLE MOTOR

Dimple motors are low energy actuators whose dimpled end extends outward upon actuation. These devices feature complete sealing of combustion products with no contamination of surroundings. Typical uses of these motors are as indicators and actuators of switches, locks, and releases.

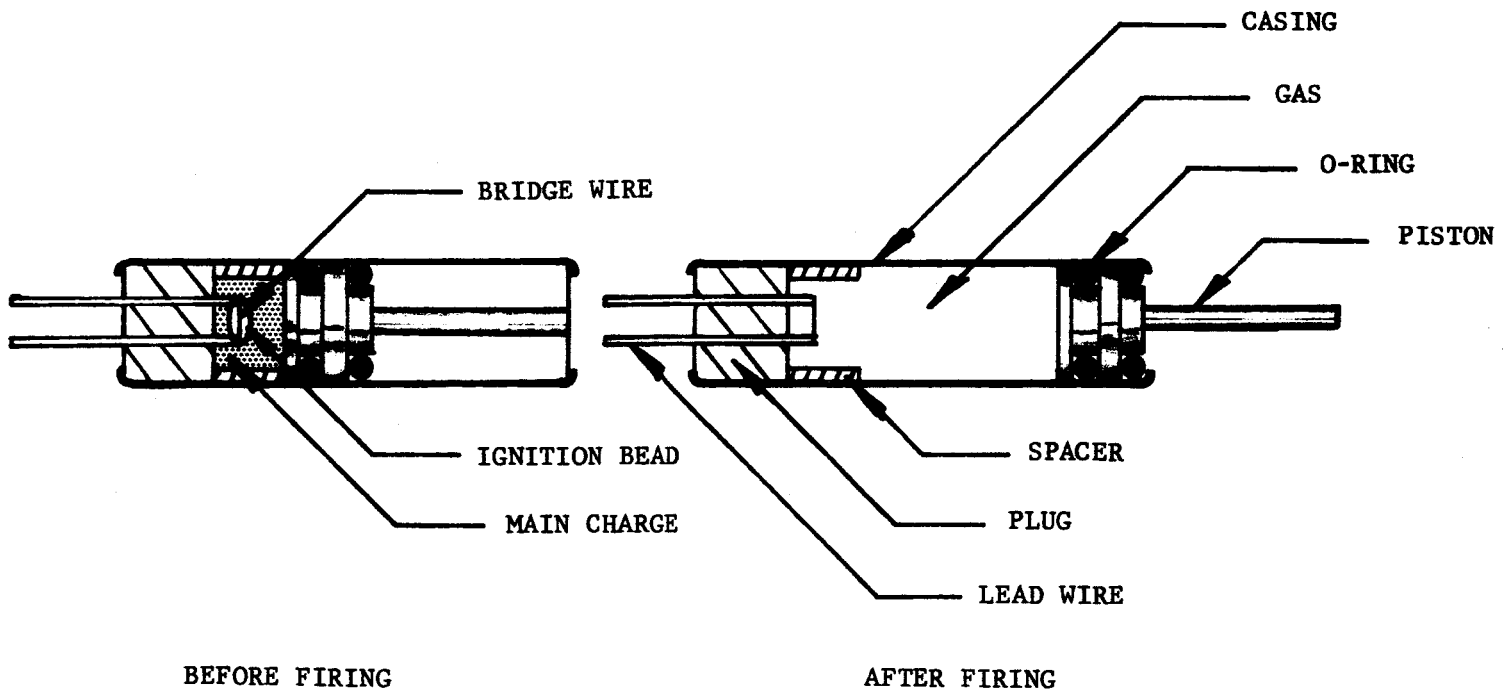


FIGURE 5. SCHEMATIC DIAGRAM OF PISTON ACTUATOR

Piston actuators are larger energy actuators than dimple motors and are characterized by a moving piston. Some lock at their extended position. Others are capable of blowing the piston free of its casing. These devices usually seal in combustion products and contamination is minimized. Uses of these devices include latch release, switch actuation, diaphragm puncture, and valving.

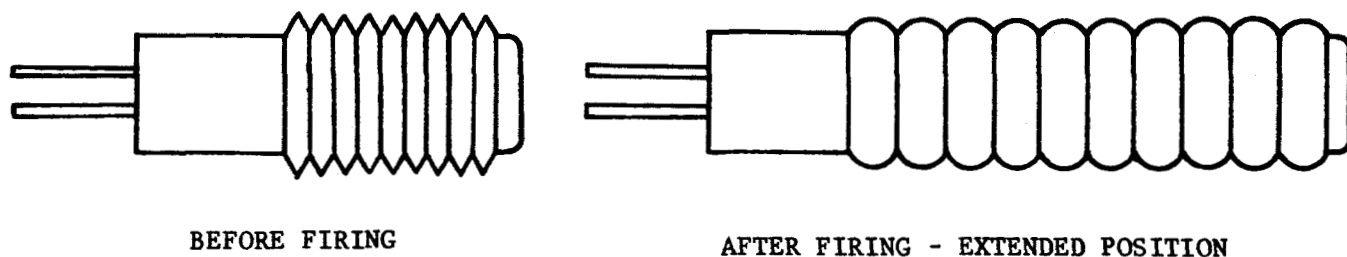


FIGURE 6. SCHEMATIC DIAGRAM OF BELLOWS MOTOR

Bellows motors are similar to piston actuators. The difference between them is that instead of a piston extending from the output end of the device, the bellows type case itself expands outward. They are self-contained and combustion products are sealed in. Due to the flexibility of the bellows, these devices can be used to start gyros and turn rotors. They also may be used to actuate release mechanisms, valves, and switches.

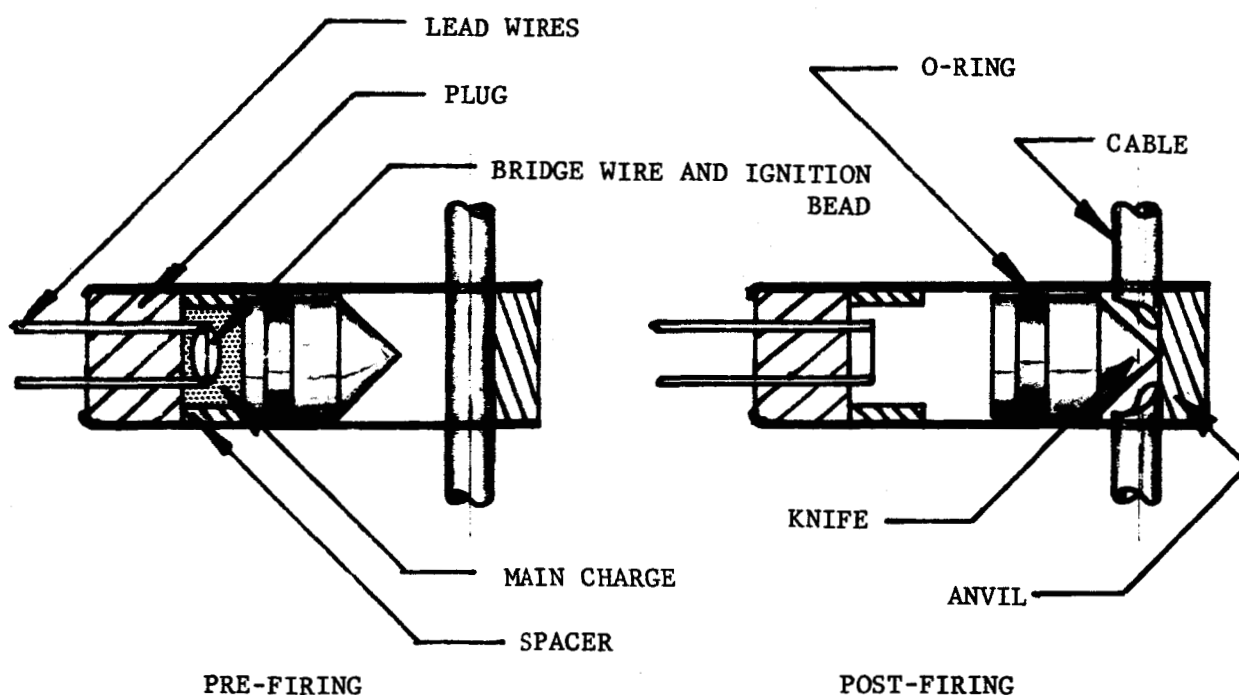


FIGURE 7. SCHEMATIC DIAGRAM OF CABLE CUTTER (GUILLotine)

Guillotines or cable cutters are devices similar in structure to piston actuators. The difference between them lies in their use. As the name implies, guillotines are used to cut ordinary or electrical cables. In place of the piston, the cable cutter contains a piston knife which drives into an anvil located at the end of the cutter's case. A hole through the case between the knife and the anvil is provided for the cable. These units are self-contained and there is little leakage of combustion products to the surroundings.

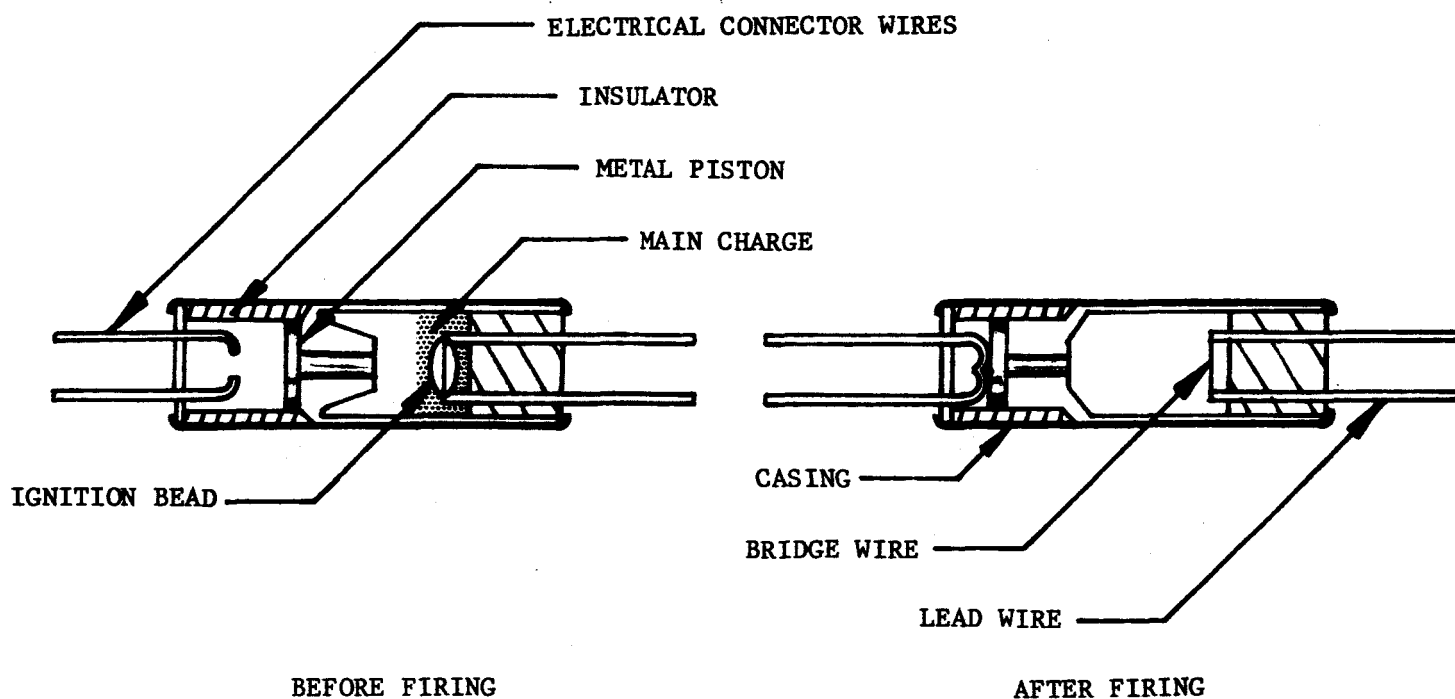


FIGURE 8. SCHEMATIC DIAGRAM OF EXPLOSIVE SWITCH

Switch actuators make up the last actuator type of explosive device. They contain small amounts of gas-producing igniter or propellant compositions. Typically, sealed-in gas pressure causes internal piston motion to open or close internal electrical contacts. Switch action may be single pole-single throw, normally closed or open, single pole-double throw, or multiple pole-double throw. Actuator requirements are varied and can be modified for specific requirements since the ignition section is usually a standard squib. Usual operation time varies from 10 to 15 milliseconds for instantaneous designs and from 20 milliseconds to several seconds for delayed action types. The switches usually have 1 to 10 ampere capacities.

Under the initiator, destruct and separation classification are higher energy devices such as primers, explosive bolts, and detonators. These devices are essentially high-energy triggers.

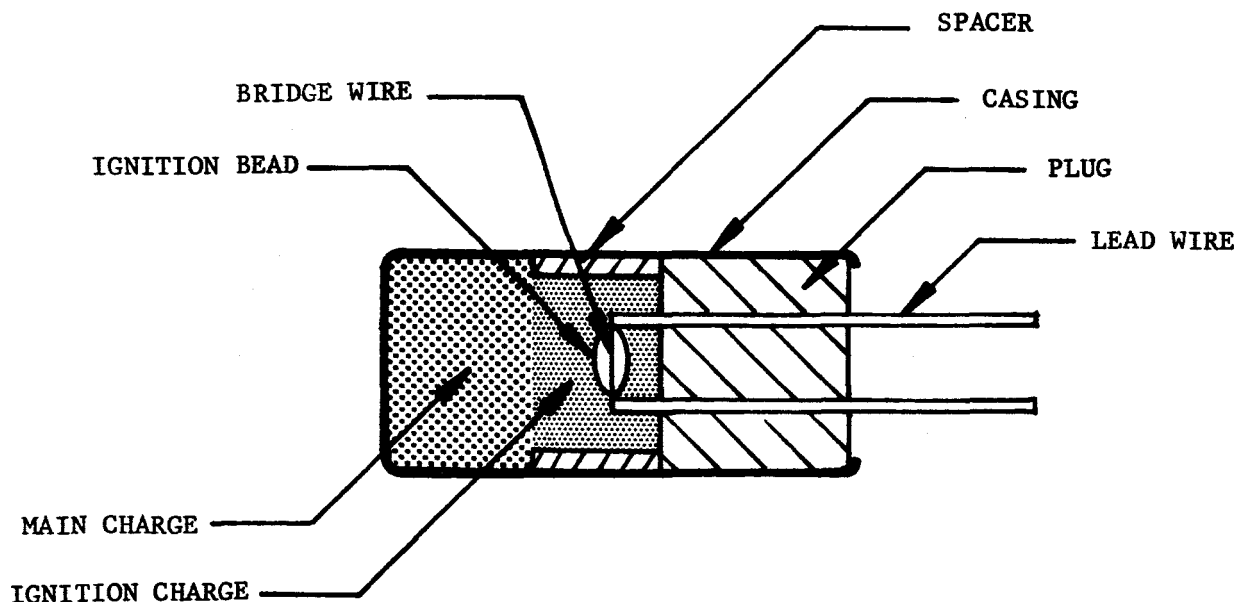


FIGURE 9. SCHEMATIC DIAGRAM OF PRIMER

Primers are used in place of pressure cartridges to obtain high-pressure gas impulses for actuating pistons, valves, etc. They find some use as igniters, but because of their high energy output are usually used as medium brisant actuators. The only consequent difference between primers and other actuators is in energy output and brisance.

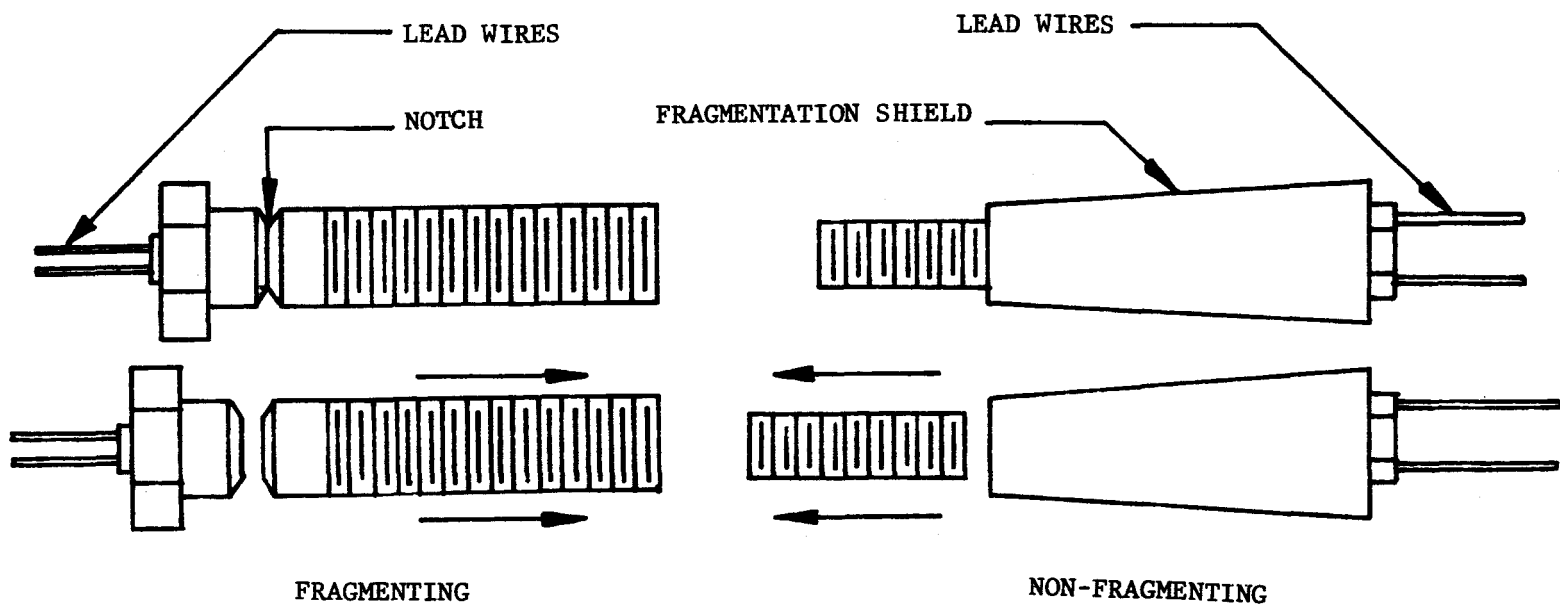


FIGURE 10. SCHEMATIC DIAGRAMS OF EXPLOSIVE BOLTS

Explosive bolts function as separation devices, and thus are used in rocket stage separation and similar applications. Explosive bolts can be fragmenting or non-fragmenting and in certain designs can be used to provide separation thrust.

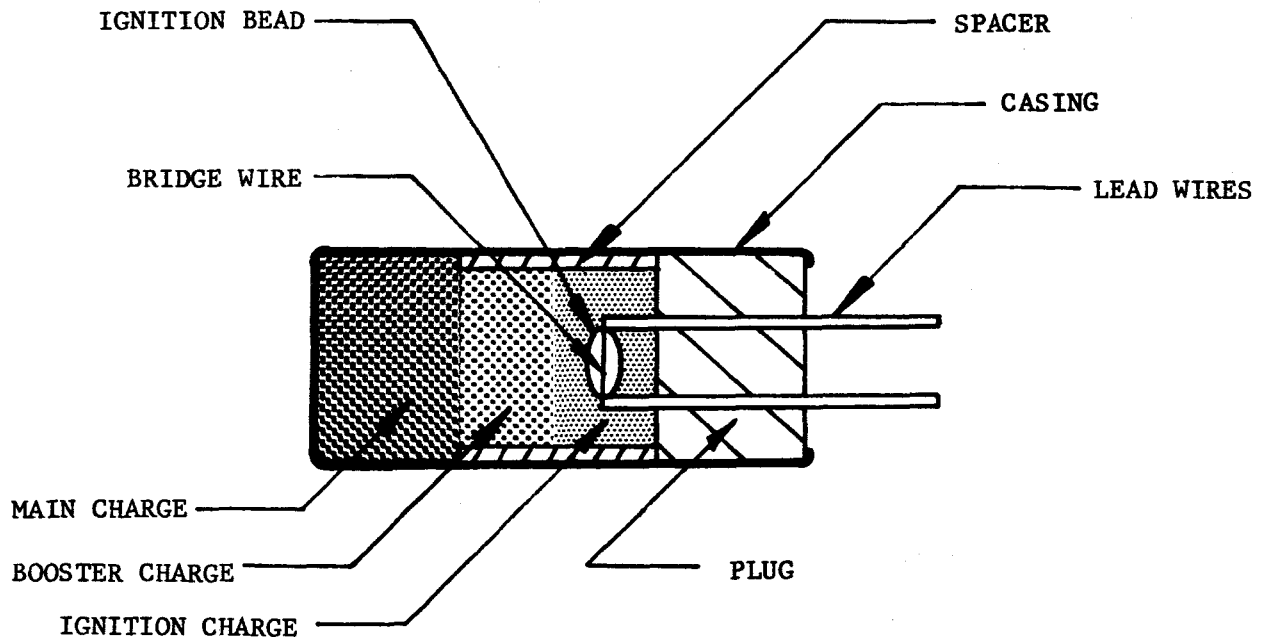


FIGURE 11. SCHEMATIC DIAGRAM OF DETONATOR

Detonators are high-brisance devices using high explosives as their main charge. They are used almost exclusively in the initiation of secondary high explosives, frequently in destruct systems and in separation applications where detonator cord is used.

BASIC MATERIALS FOR ELECTROEXPLOSIVE DEVICES

In general, electroexplosive devices are comprised of a case, lead wires, bridge wires, end closure, header or plug sealing material, and explosive charge or charges.

Casing

The case of electroexplosive devices is, with few exceptions, cylindrical. Case materials range from cardboard sleeves to machined stainless steel capsules. The type of material used depends on the function of the device and the conditions of its use. Low brisance devices such as squib igniters, pressure cartridges, and small gas generators commonly use anodized aluminum as the casing material. Gilding metal (95-5 copper-zinc), polyethylene, bronze, copper, nickel-silver (65-18), and cardboard are also used. Of these materials, gilding metal is almost as widely used as aluminum. Bronze casings are used primarily for delay models where high sustained heats are generated. Threaded cases having hex heads are made of brass and various steels. These extra strength cases allow the unit to function normally without side bursting when the case is not well supported.

Dimple and bellows motors both use brass in the expanding portion of their cases with gilding metal (outside) and steel (inside) sleeves to prevent leakage and side burst. The use of sleeves in pressure cartridges, igniters, and squibs enables them to use the softer metal cases mentioned earlier. Piston actuators use steel or cast aluminum cases with either steel or aluminum pistons. Gilding metal casings can be used in high energy devices, but an inside sleeve is used for reinforcement.

Detonators and primers generally have cases made of stainless steel or steel with cadmium plating. Other materials used include aluminum, bronze, and gilding metal.

Explosive bolts are regular commercial bolts with explosive charges inside or, in non-fragmenting types, with a ductile (AISI 4130) steel separation sleeve over the stud.

1. Aluminum (anodized)
2. Brass (nickel-plated)
3. Bronze
4. Cardboard
5. Copper
6. Gilding metal
7. Nickel-Silver (65-18)
8. Plastics, typically polyethylene
9. Steel, AISI B-1113, various surface finishes
10. Steel, 304 stainless
11. Steel, AISI 4130
12. Steel, 17-4 PH stainless
13. Steel, 303 stainless

TABLE I. CASING MATERIALS

Lead Wire Materials

The main selection criterion for lead wire material in EED's lies in whether the device has a threaded or plain case. For threaded casings, solid metal pins are used, especially if the device has a dual circuit. Non-threaded units, especially single-circuit devices, most often use solid wire leads. Stranded wire, which is harder to seal, is sometimes used.

<u>Pins</u>	<u>Wires</u>
1. Brass	1. Copper
2. Copper	2. Magnet (AWG)
3. Koval	3. Nickel
4. Nickel-Iron	4. Steel
5. Steel	5. Stainless Steel

TABLE II. LEAD WIRE MATERIALS

Bridge Wire Materials

Bridge wire size and material is determined by the electrical resistance desired across it. Wire size ranges from .0005 to .004 inches in diameter. Resistance ranges from .30 to 3 ohms per bridge. Exceptions are graphite and air gap bridge circuits which have resistances of several thousand ohms. These bridge circuits are heated or exploded by high voltage pulses from a capacitor and are used primarily in detonator circuits.

1. Air gap, typically .090 in.
2. Colloidal graphite
3. Nickel chromium iron alloy
4. Platinum-iridium
5. Platinum-rhodium
6. Seccn No. 422 (McCormick Selph Co.)
7. Tungsten

TABLE III. BRIDGE WIRE MATERIALS

Header or Plug Materials

The header or plug is an important structural part of electro-explosive devices. The lead wires, passing through it into the explosive charge must be sealed sufficiently well to withstand back pressure caused by firing. The header also must withstand environmental conditions without losing its sealing capacity.

The most commonly used seals are glass to metal or ceramic. These types of seal are almost standard on threaded case devices, especially if the leads are metal pins. Glass and threaded metal plugs are used, the sealing around the lead wires being glass to glass or glass to metal. These plugs can withstand large back pressures.

Cases of thin cylindrical tubing such as aluminum, gilding, or other softer metals use various molded plugs, phenolic resin plugs being the most popular. This type is used exclusively in unthreaded case models and has the case pressed around it. The plugs bond to the leads, eliminating the need for a glass seal.

- | | |
|-------------|--------------------------------------|
| 1. Bakelite | 5. Phenolic Resins |
| 2. Ceramics | 6. Polyethylene |
| 3. Monel R | 7. Epoxv and other potting compounds |
| 4. Nylon | 8. Rubber |

TABLE IV. HEADER MATERIALS

Good header sealing is important in preventing contamination of both EED's and their environment. Glass to metal headers form their own seal around the leads and at the case wall. Metal headers are usually soldered or, for high pressure seals, welded to the case with glass to metal seal around the lead pins. Glass plugs and ceramic plugs are fused to the leads and case. Organic or phenolic

headers are sealed by crimping the case around them or by use of interference fits in low-pressure applications (igniters). An epoxy resin coating is used as an additional seal for organic and phenolic headers. Plastic headers are heated to make them bond to the leads and case, forming their own seal.

Closure of Electroexplosive Devices

The closure at the output or firing end of an EED usually consists of a metal disc fastened into place and sealed by epoxy resin or welding. Aluminum discs, varying in thickness from 0.260 to .0015 inches, are used in squibs, gas generators, pressure cartridges, and primers to provide protection from the environment. They also seal pressure inside the EED to cause better initial burning before the disc bursts. Discs of beryllium-copper and pyrophoric materials have also been used. Detonators usually use stainless steel discs welded into place or use cases with integral ends on them. In diaphragm and bellows motors, the movable brass shell is the end closure, while in linear actuators, a piston with "O" ring seals is the closure.

Igniter Explosive Charge

The igniter charge of an EED must be a primary explosive if it is to be ignited by a heated bridge wire. This initial charge ignites less sensitive explosives in the device.

The basic igniter charge used by the industry is a lead styphnate bead encasing the bridge wire with lead azide packed around this. Mercury and lead fulminate are sometimes used as the bead charge, but because of their greater sensitivity to heat, their use is limited. Lead styphnate and lead azide are frequently used individually as ignition charges. Other ignition charges include:

- | | |
|------------------------------------|------------------------------|
| 1. A-5 Black powder (duPont) | 6. LMNR/chlorate |
| 2. Borium chromate/zirconium | 7. Lead/selenium/nitrostarch |
| 3. Boron-potassium nitrate (23/70) | 8. Lead styphnate/selenium |
| 4. DDNP | 9. Zirconium/potassium |
| 5. DDNP/potassium chlorate | perchlorate |

Booster Charges

When the EED has a main charge of low sensitivity or when it is

fairly large, a booster charge is sometimes used. The booster charge raises the heat and pressure allowing the main charge to burn more efficiently. Detonators often contain booster charges, typically of lead azide.

Main Charge

The material which makes up the main explosive charge of an EED imparts to each device its particular performance characteristics. Various explosive materials used as main charges by the EED industry include:

Main Charges

Ammonium perchlorate	Lead thiocyanate, potassium
Barium chromate/zirconium	chlorate, charcoal, egyptian
Barium nitrate and zirconium	lacquer
powder (40/60)	Potassium perchlorate/cellulose
Granular zirconium, atomized	nitrate
aluminum, aluminum flakes,	WC-860 ball powder (Unidynamics)
barium flakes, potassium	A-5 black powder
perchlorate, and binder	FFG black powder (Holex)
(igniter mix)	5066 smokeless powder (duPont)
Lead azide (primers)	
Lead mononitroresorcinate (LMNR)	

Explosive Bolt Charges

Gas-Producing Charges

Hercules smokeless powder
Lead oxide/boron
PETN (class II)

LMNR Chlorate
Lead/selenium/nitrostarch
LMNR potassium chlorate (60/40)
LMNR black powder
3FG black powder
Hercules smokeless powder

Detonator Charges

DDNP/PETN
DDNP/potassium chlorate
Lead azide
Lead azide/PETN
PETN
RDX

TABLE V.

Electrical Systems of EED's

The most common electrical system used in EED's at the present time uses a heated bridge wire. In its simplest form, it consists of two lead wires with a high-resistance bridge wire fastened between. By sending sufficient current through this circuit, the heat generated in the bridge wire ignites a primary explosive. This circuit, while simple and easy to make, has limitations. Sometimes

the circuit burns out before ignition. Stray currents, RF, or other electrical disturbances can energize the circuit enough to cause misfiring.

To eliminate the possibility of malfunction or misfire, most EED's provide dual circuits with no-fire capabilities of one ampere, one watt. Many present devices do not meet the one ampere, one watt requirement (typical sensitivity 1/2 ampere NFC, 2.0 AFC) and consequently are not qualified for many military uses. Shunting of the leads and wrapping the devices in metal foil helps to prevent misfire accidents.

More sophisticated and reliable variation of the heated-bridge type circuit use parallel bridge wires, dual circuits, and metal pins instead of lead wires. If one circuit is defective, the unit can still fire when energy is supplied by the other circuit. Parallel bridge wires allow the circuit to operate if one of the bridge wires becomes broken.

Some firing circuits contain a "continuity" loop. This merely provides a way of checking whether an EED has been fired (an open circuit indicates that the continuity loop has melted; the unit has been fired). Such loops are useful in systems check-out before launch.

In trying to provide more protection against malfunction, some manufacturers have developed a spark gap circuit to replace the conventional bridge wire. In this circuit, used primarily in detonators, a capacitor of approximately 2.0 micro-farads is charged with about 100-200 volts and discharged across an air gap in the EED to generate the needed heat and pressure for ignition. The air gap considerably lessens the chance of stray currents firing the unit because of the high energy required by this scheme.

A further development of the spark gap idea is the exploding bridge wire circuit (EBW). The energy needed to explode the bridge wire is supplied by a capacitor and switching circuit. The capacitor is rapidly discharged, producing a current pulse rise time of less than one microsecond and a current density greater than one million amperes per square centimeter in the wire. Due to skin-effect,

the current is initially confined to the wire's surface, causing the wire to melt from the surface inward.

The current pulse produces a magnetic field concentric with the bridge wire which exerts an inward radial pressure (pinch effect). This, together with surface tension, causes molten beads of material to form. During this period, the effective surface temperature of the molten metal may exceed 5,000°F. When the molten globules separate and current ceases to flow, the molten particles accelerate in random directions. The resulting high temperature, high pressure, and shock wave cause direct initiation of properly processed explosive materials.

The EBW circuit is sensitive to transmission line losses and variations in bridge wire behavior. Certain types of bridge wires such as tungsten are strongly affected by impurities which can cause variable wire behavior. Transmission line efficiency is best when there is minimum current density, making it difficult to transmit the high density current pulse without large power losses.

A comparison of EED electrical systems is given in Table VI.

ADVANTAGES

<u>Heated Bridge Type</u>	<u>FBW Type</u>
1. simple	1. needs no primary explosive charge
2. lightweight	2. insensitive to normal stray currents
3. cost	3. more reliable

DISADVANTAGES

1. Must use only primary explosives which require only application of heat for ignition.	1. Bridge wire material may effect operation.
2. Requires greater handling and storage care, due to the use of primary explosives.	2. Transmission line losses may cause changes in firing behavior.
3. High sensitivity to small currents (i.e., stray currents and voltages can fire it).	3. More complex circuit (switching pulsing circuit) needed.
4. Exhibits variations in all fire performance (i.e., may fire long before or after stated firing current is reached).	4. More expensive.

TABLE VI.
COMPARISON OF EED ELECTRICAL SYSTEMS

COMPANIES MAKING ELECTROEXPLOSIVE DEVICES

Aircraft Armaments, Inc.
Cockeysville, Maryland

Aircraft Armaments, Inc. produce sealed initiating devices which they call telecartridges. They are similar to bellows motors, but their displacement is greater and more force is developed. They range in size from 0.38 inches in diameter to 2.8 inches in diameter. Energy ratings vary from 3 to 4,000 ft.-lbs. The maximum cartridge extension is 12 inches. The units can be fired either mechanically or electrically with NFC of 0.5 amperes and AFC of 1.5 amperes. Other characteristics are dependent on the design. These units have been applied to linear actuators, separation bolts, ejectors, and liquid dispensers.

Amcel Propulsion Company
Asheville, North Carolina

Amcel Propulsion Company produces EED's to customer specifications with only two or three standard units. They specialize in development work on new requirements for initiating devices. Their standard detonator is a 1 ampere, 1 watt NFC type, with space environment capability. It operates within the temperature range from -65° F to 400° F, with auto ignition at 500° F. Amcel's standard igniter has similar characteristics.

Atlantic Research Corporation
Alexandria, Virginia

Atlantic Research produces squib igniters, pressure cartridges, blasting caps, detonators, primers, gas generators, explosive bolts, dimple motors, bellows motors, and explosive switches. Their basic design uses a thin one-piece metal case (usually aluminum) with a phenolic or similar plug-type header. Sealing is accomplished by crimping the case around the plug and doping it with epoxy resin. Metal sleeves are used inside the case to strengthen side walls in high-performance devices. Some threaded case models are available and use standard glass to metal seals and pin connectors. Generally,

the single-heated bridge wire lead circuit is used, though double bridge circuits are available. Standard firing current ranges from 0.5 to 2 amperes, with typical functioning times of 0 to 10 milliseconds. The standard operating temperature range is from -80° F to 240° F, with some models capable of operation at 400° F. The altitude range for the EED's operation is not given in company literature. Operating characteristics are described in terms of pressure/vol., hole burned in styrofoam block, graphs of pressure versus volume, or motion against determined force.

Atlas Chemical Industries
Wilmington, Delaware

Atlas produces detonators, squib igniters, small gas generators, piston actuators, bellows motors, dimple motors, cable cutters, multi-pole switches, primers, and explosive bolts. They use a unitized single unthreaded case design with a crimp sealed rubber (or similar material) plug-type header. The majority of their EED's use lead wires instead of plug-in pin leads. A glass seal is used around the lead wires in some models. For strengthening the case in high-pressure applications, metal sleeves are used inside. The electrical system in general use is the single circuit, single bridge wire type. They have some units (bellows motors, squib igniter, piston actuator) available which can pass a 1 ampere, 1 watt safety requirement without misfiring. A number of detonators use a single pin connection with the case itself acting as ground. Standard AFC is 1 to 2 amperes with NFC variable. Capacitor discharge ignition systems are used for the detonator circuits. The normal operating temperature range given is -65° F to 165° F. An interesting Atlas design is their retractable actuator. This linear actuator diverts the combustion gases so as to pull the piston back into the case. It will retract against a 20 pound pulling force.

Bermite Powder Company
Saugus, California

Bermite produces igniters, pressure cartridges, explosive switches, explosive bolts, safe-arm devices, and many other

explosive devices as well as explosive materials. These products, however, are developed to meet individual specifications; the company has few standard items. Bermite's explosive bolts operate with a firing current of 0.5 amperes to 2.0 amperes, with 99.98% demonstrated reliability at 90% confidence level. They are regular bolts with an enclosed charge and notched break point. The design indicates that fragmenting can occur at actuation, the degree of fragmentation depending on the effectiveness of the notch.

Eagle-Picher Company
Joplin, Missouri

Eagle-Picher produces gas generators to displace electrolyte into batteries. The basic design incorporates an anodized aluminum case with an aluminum header plug. Their approximate size range is from one to two and one-half inches in length, with a .375 inch diameter. The weights of these units is less than ten grams. The larger generator sizes have threaded ends for installation and plug-in electrical receptacle. They are hermetically sealed, a feature which is not available in smaller units. All of the gas generators use other companies' squib igniters for ignition and have firing characteristics of AFC from 0.6 ampere to 4.0 amperes. The majority of the generators fire at less than 1.0 ampere. Performance is rated by the amount of electrolyte displaced, ranging from 130 cc. to 8,000 cc. Operating temperature and pressure are not generally given in their catalogs, but the usual temperature range is from -65° F to 165° F for such devices.

E. I. duPont de Nemours Company, Inc.
Wilmington, Delaware

The duPont Company produces igniter squibs, pressure generating squibs, detonators, and blasting caps. Their basic design uses a thin extruded case of bronze or aluminum with a crimped sealed header. Unit sizes range from 0.375 length by 0.191 inches diameter to several inches length by 0.272 inches diameter. Wire leads and a single-circuit, single-bridge ignition system are used

exclusively. The heated bridge wire circuit has AFC of less than 1 ampere in all models listed. No standard 1 ampere 1 watt unit is available. Performance characteristics are varied, covering low and high temperatures and various altitude requirements.

The duPont Company is producing a miniature detonator (0.0018 cu. in.), called the Minidet, which is capable of initiating tetryl over an air gap of 35 mils. The Minidet will function at chosen energy levels from 800 to 50,000 ergs (0.1 to 1.0 microfarad and 40 to 100 volts) and uses the EBW circuit. It can also be made to fire at 1 ampere or be "arc-fired."

Gould Laboratories
Pitman, New Jersey

Gould produces four standard pressure cartridge series with either a plastic or metallic hermetic header seal. The basic case design incorporates a threaded body with hex head and plug-in type electrical receptacle. Some cartridges have both sides of the hex head threaded. Gould uses single and dual circuits with and without continuity loops. Dual circuit models contain the continuity loops. Each circuit has parallel bridges. Standard firing current is 2.0 amperes and no-fire is 0.5 amperes for all models. Each series has altitude capabilities of 200,000 ft. or more and the operating temperature range is -85 F to 200 F. Output is measured by pressure developed in a test chamber.

Hercules Powder Company
Wilmington, Delaware

Hercules produces small igniters, pressure cartridges, gas generators, explosive switches, dimple motors, bellows motors, primers, detonators, piston actuators, and explosive bolts. Modifications of these as well as other devices are available on individual request. Hercules designs generally use an unthreaded cylindrical metal case with a phenolic header plug. The case itself forms the end closure and can be made to be non-fragmenting. The electrical circuits usually use lead wires in preference to pins,

pins being used mostly with the threaded case models. Two-wire single-bridge circuits are used most commonly; a three-wire, two-bridge circuit is used in some primers for higher reliability. Condenser-fired carbon bridges and EBW circuits are also used, however, heated bridge wire circuits are the general standard. Functional characteristics vary from unit to unit. General operational limits range from -65° F to 160° F for temperature, 0.5 to 4 or 5 amperes AFC, 1 to 10 milliseconds for operation of instantaneous devices, delay times from milliseconds to several seconds, and altitude limitations of from 60,000 feet or less to 4 mm of Mercury. The explosive output of Hercules' EED's is measured in sand crushed, flame, liquid volume displaced, dent size in a slab of metal, or pressure/volume, depending on the device and the property demonstrated.

Hi-Shear Corporation
Torrance, California

Hi-Shear produces detonating cartridges, gas generating power cartridges, guillotines, and separation nuts. Both the ordinary gas cartridge and detonator have 1 ampere, 1 watt NFC capability, and the gas cartridges use the EBW system. All use dual bridge circuits. The standard design is hex stock, which is threaded at one end and has a mating connection at the other. The aluminum header is brazed to both the lead pins and the case and is hermetically sealed. The closure is a steel disc welded in place. All the units will operate in a vacuum and have an operating temperature range of from -80° F to 185° F. The gas cartridges are available in various sizes and outputs. Output is measured as pressure per test volume. Average pressure ranging from 630 to 15,500 psi.

Holex Incorporated
Hollister, California

Holex produces squib igniters, pressure cartridges, ignition primers, guillotines, linear actuators, explosive bolts, and explosive switch and valve devices. The basic design for their

igniters, ignition primers, and pressure cartridges incorporates a threaded steel hex body with glass to metal header seals and an epoxied or soldered steel closure. Pin leads are commonly used, though some of their igniters come with lead wires, and single or dual circuits are available. Horex uses the heated wire ignition circuit with parallel bridge wire available on some single-circuit models. Pin to case insulation is 2 megohms at 500 volts direct current. Usual operation time of their devices is 5-10 milliseconds with "no-fire" current at 0.5 to 1.00 amperes and "all-fire" current at 2 to 4 amperes. Horex has recently adapted some of their pressure cartridge units to the 1 ampere, 1 watt "no-fire" requirement but has not at this time shown any EBW models. Performance characteristics are measured in foot-pounds of energy with usual operating conditions at -65° F to 250° F, or at -300° F, 25,000 ft. altitude to perfect vacuum condition. Horex explosive bolts are fragmenting with the charge inside. Its linear actuators use a standard pressure cartridge threaded into a piston with a cylindrical case. Horex does specialized design suited for specific requirements. Most fabrication is sub-contracted.

Jet Research Center, Inc.
Arlington, Texas

Jet Research produces and stocks small electric squib igniters, pressure squibs, detonators, and various fuses and delay elements. It also produces special squibs and detonators, cartridge actuated devices, bellows motors, dimple motors, and delay cartridges for specific applications. The basic design of the "shelf" items is a thin metal case with a crimped-in phenolic header plug. Wire leads are used, and the typical size is 0.37 inches long by 0.27 inches diameter. Output is measured by the damage done to a lead plate on firing.

Librascope
Sunnyvale, California

Librascope produces squib igniters, detonators, blasting caps,

and thrust termination sectors. Their basic design uses a threaded hex case with either bayonet or screw-type connectors. Most of the units incorporate glass to metal headers with hermetic sealing. Usual unit size is 1.00 inch length with 0.625 inch hex head. Librascope generally uses the EBW type circuit. However, units are available which are capable of low voltage or 1 ampere, 1 watt firing specifications. Since the units are hermetically sealed, they will operate in hard vacuum with no loss of reliability. The EBW circuit allows exclusive use of secondary explosives. Consequently, the operating temperature range of their units varies from -75° F to 850° F, with auto-ignition at temperatures in excess of 950° F. The chief feature of Librascope's EED's is in their use of the EBW to decrease the danger of misfire. Their devices with EBW can be used without safe-arm devices. They are insensitive to external electrical pulses less than 9,000 volts from 500 micro-farad capacitor.

McCormick-Selph Associates, Inc.
Hollister, California

McCormick-Selph produces squib igniters, gas generators, pressure cartridges, detonators, piston actuators, and explosive bolts. Their basic design uses a threaded hex case with either screw-in or bayonet-type connectors. The header seal is glass to metal and the end closure is a sealed metal disc. Pin-type leads are used in a majority of the units. Both dual and single electrical circuits are available, the single circuit using the case as ground. The explosive bolts are non-fragmenting, using a metal fragmentation shield design and threaded connectors. McCormick uses single and double heated bridge wire circuits, a 1 ampere, 1 watt circuit, and EBW circuits. The EBW circuit incorporates an air gap in series with the bridge, making the circuit insensitive to low-energy stray currents and radiation. Operation time for heated bridge circuits is from 0 to 10 milliseconds. EBW's operate in microseconds. Performance characteristics are shown graphically in company publication. Output is measured in "psi" per test chamber volume for pressure devices, and pounds force for piston actuators. Operational temperature range for the standard units is

from -65° F to 200 ° F, with one igniter capable of 1,100° F operation. McCormick-Selph has designed Through Bulkhead Initiators. These units transmit explosive force through a bulkhead to ignite explosive material on the other side. They are non-electric, fast acting, insensitive to stray RF, and eliminate back leakage.

Olin Mathieson Chemical Corporation
East Alton, Illinois

Olin produces a wide variety of pressure cartridges and igniter squibs as well as a few primers and thermal switches. However, their production concentrates on large-size gas generators using an ammonium nitrate composition as the chief ingredient. Small EED's are in the process of development, the first 1 ampere, 1 watt igniter squib being put into production February of 1963. The design features a unitized body with metal header. They have similar models with threaded case and hex head top. A good design feature is the cross coined case bottom, which, weakening the bottom, prevents case fragmentation. Most units use wire leads. There are few plug-in models. Only preliminary specifications are available on their detonators, high temperature primers, high pressure and temperature pressure cartridges, and miniature igniters. They indicate the use of single-unit unthreaded cases (the pressure squibs are converted to the standard threaded hex stock case with pins).

Olin's ignition systems general use the single-bridge circuit. Some new models use dual-bridge circuits. There is no indication of work with exploding bridge wire circuits. The standard environmental temperature range of operation is from -65° F to 200° F, with some models capable of withstanding 500° F.

Ordnance Engineering Associates, Inc.
Chicago, Illinois

At the present time, Ordnance Engineering Associates produces gas generators, a ballistic pulser, and several special cartridges using RDX for the main charge. Their gas generators vary in length from 3.7 inches to 4.6 inches and weigh from 0.30 lbs. to 0.41 lbs.

The ballistic pulser produces a sine shaped thrust-time curve and is available with thrust ratings from 50 lbs. to 800 lbs. Pulsers range in size from 2.81 inches in length by 1.50 inches in diameter to 11.34 inches in length by 2.00 inches in diameter. The pulser operates from -65° F to 160° F, with pulse duration of 7 to 100 milliseconds. It is fired by 160 volt capacitor discharge.

Rocketdyne
Canoga Park, California

Rocketdyne's present capabilities include the manufacture of rocket motors, gas generating devices, igniters, and propellants. Rocketdyne does not engage in manufacture of small EED's and most of the igniters range upwards in weight from one pound. Output is measured in BTU's.

Special Devices, Inc.
Newhall, California

Special Devices, Inc. produces squib igniters, pressure cartridges, detonators, guillotines, explosive bolts and nuts, explosive switches, piston actuators, bellows motors, and flares. Their basic design of igniters and pressure cartridges uses a threaded hex body 0.625 inches across the flats. The average length is approximately one inch. Pin-type connectors are used on threaded models. The detonators, small squibs, piston actuators, and guillotines have unthreaded cases and wire leads. Special Devices' explosive bolts are regular bolts containing an explosive cartridge. The bolt is notched to reduce fragmentation. The explosive nuts fragment. Most of the devices use heated bridge wire circuits with two bridge wires in most models. However, some pressure cartridges use exploding bridge wires. Usual operating temperatures range from -65° F to 165° F; some devices can operate at 200° F. The usual altitude limit is 100,000 ft. An interesting feature of Special Devices' linear piston actuators is that they have a very short stroke (about .40 inches maximum), and the combustion products are completely contained after firing.

Unidynamics
St. Louis, Missouri

Unidynamics produces gas generators, squib igniters, piston motors, detonators, explosive switches, and pressure cartridges. Their standard units are gas generators and squib igniters. Most use threaded cases and hex tops for simple initial installation. Sealing is the glass to metal, and both dual and single bridge wires are used. Igniters and initiators capable of operation at 300,000 ft. altitude are available. Their detonators are capable of reliable performance in extreme conditions.

An interesting Unidynamics design is their dual system gas generator incorporating two smaller generators mounted side by side in the same unit. As a result, it can be used twice, once for each generator. The generators are on separate firing circuits and can be initiated by DC current, capacitor discharge, or percussion, depending on requirements.

Unidynamics has units capable of functioning from -100° F to 700° F under vacuum conditions. Output is measured as pressure force developed in prescribed chamber size.

In compiling the information given above, no response was received from written inquiries to the following companies:

Eaton Chemical Corporation Trenton, New Jersey	Pacific Match Company Tacoma, Washington
Fidelity Electric Company, Inc. Lancaster, Pennsylvania	Pacific Powder Company Seattle, Washington
General Machine and Instrument Co. Caldwell, New Jersey	Pringle Powder Company Bradford, Pennsylvania
Hanley Industries, Inc. St. Louis, Missouri	Propellex Chemical Division Edwardsville, Illinois
Humble Oil and Refining Company Houston, Texas	Sargeant and Wilbur, Inc. Pawtucket, Rhode Island
Hunter-Bristol Division Bristol, Pennsylvania	Space Ordnance System, Inc. El Segundo, California
Lake Superior Safety Fuse Company Eagle River, Michigan	Texas Torpedo Company Electra, Texas
National Powder Company Eldred, Pennsylvania	Thiokol Chemical Corporation Trenton, New Jersey
Nelson Industries Pittsburgh, Pennsylvania	West Coast Powder Company Everett, Washington

MINIATURIZATION OF EED'S

The development of EBW systems has increased the safety and reliability of EED's, and is the key to further miniaturization of these devices. By use of an EBW circuit, the primary charge can be eliminated, in addition to the elimination of out-of-line safe-arm devices, if the device is used in an explosive train. Consequently, double base propellants such as nitro-glycerine, nitro-cellulose, and cordite can be ignited directly. It is desirable to use these explosives because of their high efficiency. They also give low-temperature, clean combustion products upon ignition. Double-base propellants average burning rate is 0.1 inches/sec., well below the rate of detonation.

Other choices of explosive charge include high density, high-impulse propellants. These have a density of about 0.1 lb/in.³ and have a specific impulse of 190 lbs.-sec./lbm, a 50-60% increase in impulse over HEX 12. However, such propellants are highly corrosive and give a high-flame temperature of about 6,500° F on ignition. Another alternative is the use of secondary high explosives, such as PETN and RDX, as the explosive charge. A problem in the use of these explosives involves what is called a "critical diameter", i.e., in small quantities the explosive performance is unpredictable. It may explode or deflagrate, depending to a great deal on the pressure around it. Low pressure usually causes the explosive to deflagrate rapidly, while high pressure helps maintain the explosion-type reaction. It is noted that relatively shock-sensitive materials such as PETN, HEX, and RDX, generally exhibit a smaller "critical diameter" than those that are shock insensitive such as TNT. Consequently, they can be used in smaller quantities before their performance loses reliability.

Mechanical shock and vibration can cause "hot spots" in explosive materials, causing ignition. These "hot spots" are about 10^{-3} to 10^{-5} centimeters in diameter. They produce a temperature of 500° C (832° F) for 10^{-4} to 10^{-6} sec. in both primary and secondary explosives. The causes of "hot spots" include:

1. adiabatic compression of small entrapped gas bubbles

2. friction at the surface of the containing walls, or foreign particles between the crystals of explosive.
3. viscous heat generation.

OTHER INITIATING SYSTEMS

Other initiating systems now being developed include film resistor initiators, conductive mix systems, and spark gaps using powdered metal conductors.

When the bridge wire is replaced by a metal film, the resistor surface area is independent of the total resistance. Voltage and current insensitivity is provided simultaneously.

In the conductive mix ignition system, metallic-conductive mixes doped with graphite show promise. The A.R.D.E. of the United Kingdom is developing a conductive mix system operating from a high voltage source of limited current capacity.

Armour Research Foundation has developed a low-energy detonator which uses a mixture of RDX and acetylene black as the initiating composition. An air gap is employed which facilitates transition from deflagration to detonation by requiring a fixed energy level to be reached before the circuit is closed. The duPont Company, as noted earlier, has a similar miniature device.

Finally, the inclusion of powdered iron within an EED can attenuate stray RF signals and provide some protection against misfire.

REMARKS ON THE EED ART

After surveying company catalogs and other literature, we conclude that the EED industry is sorely in need of standardization of terms and output characteristics. There are no industry-testing standards or procedures, and each company describes its devices so as to make them look best. For example, the term "squib" may refer to a class of explosive devices, to a small igniter, or to a small gas generator. Output measurements may be described in foot-pounds force or the size of a dent made in a steel plate. The result is total confusion about the relative capabilities of devices made by various companies.

Military environmental requirements have forced individual companies to conform partially to a standard. Hill Air Force Base is studying safety reports of "in-service" devices and plans to develop safety specifications that each device must meet.

GLOSSARY

AFC	An abbreviation for All Fire Current, i.e., the current which will reliably initiate the explosive device.
BACK PRESSURE	The internal pressure exerted on the header and top of the case when the device is fired.
BELLOWS MOTOR	A non-brisant device formed by a thin cylindrical shell sealed to a bellows. When an internal gas-producing mixture is ignited, the contracted bellows expands longitudinally with considerable force.
BRIDGE WIRE	The part of an EED which corresponds to the filament in a light bulb. Its heat ignites the powder charge.
BRISANCE	The shattering effect of an explosive.
CLOSURE	The end seal on the casing of an EED.
COOK-OFF-TEMPERATURE	The temperature at which the explosive begins to decompose. Similar to auto-ignition temperature. The explosive becomes chemically unstable.
DEFLAGRATION	The relatively slow burning or chemical decomposition of a propellant. Burning rate usually less than 2,000 meters/sec. The reaction is a surface reaction.
DETONATOR	A high-explosive device which will reliably initiate other high explosives by a detonating wave or shock-front action.
DIMPLE MOTOR	A small electrically initiated non-brisant actuator which, when fired, causes the shell bottom, which is dimpled inwardly in a rounded cone shape, to move outward.
DUAL BRIDGE WIRES	This refers to an EED which has two bridge wires in parallel in the same circuit. This gives the unit redundancy since the circuit will operate if one wire is broken.
EBW	An abbreviation of Exploding Bridge Wire.
EXPLOSIVE BOLT	Fragmenting or non-fragmenting. A bolt that is fractured by a contained explosive charge.

EXPLOSIVE TRAIN	A series of explosive elements or charges starting with the most sensitive (or easily fired charge) and ending with a least sensitive. Each element ignites the element ahead of it in line, thus allowing a small EED to indirectly light a large explosive charge.
FRAGMENTATION SHIELD	A metal sleeve used around some explosive bolts to prevent fragments of the bolt from doing damage when the bolts are fractured.
GAS GENERATOR	A pyrotechnic device in which a propellant is burned to produce a sustained flow of pressurized gas.
HEADER	The end seal or plug closure where the leads connect to the casing of the EED.
IGNITER	A pyrotechnic device used to initiate burning of a fuel mixture or a propellant.
IN-LINE	A term used to describe the position of an explosive element in an explosive train. In the "in-line" position, an element will fire the next one in the train when it itself is fired.
NFC	An abbreviation for No Fire Current. The current which can be safely passed through the bridge wire of the device without initiating it.
OUT-OF-LINE	An explosive element in the "out-of-line" position in an explosive train will not fire the next element in the train when it itself is fired.
PISTON ACTUATOR	A self-contained EED whose internal gas pressure causes a piston to push out the end of the unit's case with a large force.
PRESSURE CARTRIDGE	A pyrotechnic device which produces a high-pressure impulse for an instant of time with little residual pressure.
PRIMARY OR LOW EXPLOSIVES	These explosives are those, such as lead azide, which are sensitive to heat and shock and can be ignited by heat alone. They deflagrate instead of detonating when ignited.

PRIMER	A primary initiating device to produce a hot flame. A primary stimulus-sensitive component generally used to generate a brisant output for initiating detonating compositions. Infrequently used to initiate deflag-compositions.
PYROPHORIC MATERIAL	Material capable of igniting spontaneously when exposed to air.
SAFE-ARM DEVICE	A device used to position an explosive element in the "in-line" (arm) position or the "out-of-line" (safe) position.
SECONDARY EXPLOSIVES	These explosives are insensitive to ignition by heat alone and are usually ignited by a combination of heat and pressure, usually by a shock wave. On ignition, these explosives detonate, producing heat and a high-pressure shock wave.
SIDE BURST	A malfunctioning of the electroexplosive device in which case walls burst open before the output end seal does. The cause is usually improper side support case mounting.
SQUIB	A small non-brisant pyrotechnic device to produce a limited flash or flame, or, infrequently, pressurized gas.
THRUST TERMINATION SECTORS	Units which act as rocket-thrust terminators by permitting release of a closure part, thus venting the rocket motor.
EXPLOSIVE COMPOUNDS	
DDNP	Diazo dinitro phenol, a primary explosive used as an initiator, detonator, or brisant gas producer.
LMNR	Lead mono nitro resorcinatate, a primary explosive used as an initiator or low-brisance gas producer.
PETN	Penta erythritol tetra nitrate, a secondary (high) explosive used as a detonating main charge.
RDX	cyclo trimethylene trinitramine, an organic, relatively insensitive high explosive with good high-temperature properties.
HMX	A fraction of RDX, with slightly better high-temperature properties.

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